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Michael L. Billet, et al

Pennsylvania State University

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M. L. Billet and D. S. Weir

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13. ABSTRACT

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GENERAL BACKGROUND

Ventilated cavities are cavities formed with noncondensable gas, which can be used to model vaporous cavities since the work of Reichardt (2) showed that drag and geometry are identical for a given cavitation number and model shape. In forming these ventilated cavities, two different closure conditions have been observed. These are the twin vortex and re-entrant jet regimes, and are indicative of the process which entrains the cavity contents.

Previous research in ventilated cavitation has concentrated on cavities having a large cavity length to model diameter ratio which is characteristic of the twin vortex regime (References 1, 2, and 3). This corresponds to the super-cavitating foil case. However, only the re-entrant jet closure condition has been observed to occur for developed vaporous cavitation.

Recently, two studies (References 4 and 5) have been involved with measuring the ventilated flow coefficient, defined as the nondimensional volume flowrate of the noncondensible gas, for a ventilated cavity. Both studies involve moderate cavity length to model diameter ratios so that the cavity re-entrant jet closure exists for the ventilated cavity and hence for the similar vaporous cavity.

In this paper, the variations in measured flow coefficients for a ventilated cavity in the re-entrant jet regime are investigated theoretically and compared with experimental results. These variations are due to the effects of gas diffusion and vaporization.

THEORETICAL CONSIDERATIONS

The ventilated flow coefficient defined as

$$C_Q = \frac{Q}{V \cdot D^2} \tag{1}$$

is a non-dimensional representation of the volume flowrate needed to sustain a ventilated cavity. If the volume flowrate is based on cavity pressure and ventilation is the only source of gas to the cavity, the flow coefficient becomes a function of a particular geometry. This implies that, for the same cavitation number, the ventilated flow coefficient is unique no matter what gases are forming the cavity.

From continuity considerations, the total mass flowrate through a ventilated cavity is given by

$$\dot{M}_T = \dot{M}_{VG} + \dot{M}_V + \dot{M}_{DG} \tag{2}$$

where $\dot{M}_T$ is the total mass flowrate through the cavity, $\dot{M}_{VG}$ is the ventilated gas mass flowrate, $\dot{M}_V$ is the vapor mass flowrate, and $\dot{M}_{DG}$ is the diffused gas mass flowrate. This resulting mixture behaves as a perfect gas since the vapor contribution is small for a ventilated cavity. Thus, applying the perfect gas relation to the mixture of gases, Equation 2 can be written as

$$\frac{P_T Q_T}{TR_T} \simeq \frac{P_{VG} Q_{VG}}{TR_G} + P_V\, f(T,R) Q_V + \frac{P_{DG} Q_{DG}}{TR_G} \tag{3}$$

where Q denotes volume flowrate, and the equation of state for the vapor is of the form $\rho_V = P_V f(T,R)$ since water vapor does not behave as a perfect gas. Also, 1) the ventilated and diffused gases are assumed the same, 2) the cavity pressure is assumed low compared to the critical pressure of the gas, and 3) equilibrium is assumed between the component mass flowrates, each occupying the total volume of the cavity.

The equilibrium cavity pressure is given by Dalton's Law as

$$P_T = P_V + P_G \quad .$$

or dividing the gas pressure P_G into the two contributing terms as

$$P_T = P_V + P_{VG} + P_{DG} \quad . \tag{4}$$

Substituting the above pressure equation into Equation (3) and matching similar variables, a relationship between each participant mass flowrate in an equilibrium ventilated cavity evolves as

$$\frac{\dot{M}_{DG}}{P_{DG}} = \frac{\dot{M}_{VG}}{P_{VG}} \simeq \frac{\dot{M}_V}{P_V} \tag{5}$$

where the vapor pressure is obtained at saturation conditions through steam tables.

Although the relationships developed in this paper based on ideal-gas mixtures are of general usefulness, there is a complication that must be recognized because of the saturated vapor. The partial pressure of the vapor can never be greater than the saturation pressure at the mixture temperature. Any attempt to increase the partial pressure beyond the saturation pressure results in partial condensing of the vapor.

This restricts the usefulness of the relations to problems in which the cavity pressure is large compared to the saturated vapor pressure, and hence the vapor mass is small compared to the total cavity mass. This is the case for almost all ventilated flows in water. In order to use this development for cases where the vapor pressure is the same order of magnitude as the cavity pressure and hence has a significant mass flowrate, an equation of state for the vapor is required.

The existence of each participating mass flowrate can be verified by analyzing the particular flow state. As an example, ventilation occurs only when there is an outside air supply to the cavity. Vaporization can only occur when the local cavitation number is equal to or less than the minimum pressure coefficient, $-C_{p_{min}}$, of the model. Finally gas diffusion will occur when there exists a concentration gradient between the free stream and the cavity.

The limit for the onset of vaporous cavitation can be expressed as a function of the incipient cavitation number. At cavitation inception, the cavitation number is approximately equal to $-C_{p_{min}}$ of the body, which can be expressed as

$$\sigma_i = \frac{P_\infty - P_V}{1/2\rho V_\infty^2} \leq -C_{p_{min}} \tag{6}$$

where P_∞ is the static pressure around the model, and P_V is the vapor pressure. Thus if a ventilated cavity test is conducted so that $P_\infty - P_V \leq -C_{pmin}(1/2\rho V_\infty^2)$, vaporous cavitation can possibly occur and hence vapor can contribute to the cavity mass flowrate.

Gas diffusion will occur when there exists a concentration gradient between the free stream and the cavity. This concentration gradient can be calculated from the partial pressures of the gas. The maximum partial pressure of the gas can be calculated from a knowledge of the free stream air content and Henry's law as

$$P_{FS} = \alpha \cdot \beta \tag{7}$$

where α is the free stream air content in ppm by moles and β is Henry's Law constant which depends on temperature. Then, once the partial pressure of air inside the cavity is known, the concentration gradient can be calculated.

The mass flowrate of air into the cavity by diffusion can be expressed in terms of the partial pressures as

$$M_{DG} = f(\text{transport}) \cdot \{P_{FS} - P_G\} \tag{8}$$

where f(transport) is a function of the mechanics of diffusion. A minimum amount of diffusion will occur if the gas pressure of the total noncondensible gas in the cavity, P_G, is approximately equal to the partial pressure due to the concentration of the free stream, P_{FS}.

In general, the total volume flowrate, Q_T, in a ventilated cavity is influenced by the flowrates due to the ventilated gas, Q_{VG}, diffused gas, Q_{DG}, and vapor, Q_V, if vaporization occurs. To obtain the dimensionless flowrate coefficient, Equation (1), it is necessary to determine Q_T, but Q_{VG} is the measured flowrate, thus the other participating flowrates must be eliminated, or taken into consideration.

In a ventilated flow situation, two distinct cases commonly occur: 1) there exists a partial cavity and air is added to establish a new equilibrium cavity and 2) there exists a concentration gradient between the free stream and ventilated cavity so that gas diffusion will occur. In both cases, the measured volume flowrates can vary greatly and can be different than the volume flowrate for the purely ventilated cavity.

If diffusion is occurring in the ventilated cavity, the total mass flowrate through the cavity is

$$\dot{M}_T = \dot{M}_{VG} + \dot{M}_{DG} \tag{9}$$

with the assumption that the vaporous mass flowrate is negligible. Also, the mass flowrate of diffusion can be written as a function of saturation values as

$$\dot{M}_{DG} = f(\text{transport})(P_{FS} - P_G) \; ; \tag{10}$$

however, some information about the transport function must be determined.

This transport function can be computed from a knowledge of the boundary layer over the cavity surface. In most cases, as the boundary layer forms over the nose, the structure of a laminar flow breaks down, and turbulent eddies will result, causing an increase in the mass transport ability of the boundary layer at the cavity surface. This phenomenon can be explained by Prandtl's mixing length model. The resulting increase in mass transport due to the turbulence of the boundary layer, as can be seen by the enormous increase in the apparent viscosity of the turbulent fluid, could be orders of magnitude compared to a potential flow solution. (Reference 4)

For this turbulent diffusion model, the flow over a cavity wall is represented by flow over a flat plate. As shown in Figure 1, the x-axis is placed in the direction of flow, the y-axis is at right angles, and the turbulent boundary layer has an approximate origin near the cavity formation

point. For these conditions, the boundary layer equations for incompressible flow are similar to the mass diffusion equations if the Schmidt number is unity. The Schmidt number is defined as the ratio of kinematic viscosity to mass diffusivity.

Hence it follows that if the cavity can be represented by a plane in parallel flow, the concentrations and velocity distributions are identical at the end of the cavity for a Schmidt number of unity. For the case of $C_W - C_\infty > 0$, where C is the gas concentration, the profiles are given as

$$f(y)_1 = \frac{C - C_W}{C_\infty - C_W} = \frac{u - U_W}{U_\infty - U_W}$$

and for $C_\infty - C_W > 0$, the defect profiles are given as

$$f(y)_2 = \frac{U_\infty - u}{U_\infty - U_W} = \frac{C_\infty - C}{C_\infty - C_W} \quad .$$

Thus a mathematical model can be based on this similarity. Initially, the concentration and velocity profiles are different. At the end of the cavity, the profiles are similar if the cavity length is many times greater than the momentum thickness of the boundary layer at the beginning of the cavity. This change in profile represents a loss or gain of air in the cavity. The basis of this model to describe gas diffusion was first presented by Brennen (Reference 4).

For the case of an undersaturated cavity, the velocity defect and the concentration defect profiles are given as

$$\frac{U_\infty - u}{U_\infty - U_W} = \frac{C_\infty - C}{C_\infty - C_W} = f(y) \ . \tag{11}$$

The difference between the concentration within the turbulent boundary layer at a particular position and the concentration that initially existed represents a loss of mass of air and can be written as

$$\Delta \dot{M}_{DG} = \int_0^\infty (C_\infty - C) \{U_\infty - (U_W - u)\} \, dy \ . \tag{12}$$

Integration of this relationship at x = L becomes

$$\dot{M}_{DG} = \pi D_M \{C_\infty - C_W\} U_\infty \cdot \int_0^\infty f(y) \{1 - \left(\frac{U_\infty - U_W}{U_W}\right) f(y)\} \, dy \tag{13}$$

where D_M is a characteristic cavity size parameter, U_∞ is the velocity outside of boundary layer, and C_∞ is the concentration level outside the boundary layer.

If the cavity surface is assumed straight and the ratio of momentum thickness, θ , to cavity length, L , is small, the boundary conditions are similar to the half wake flow behind a flat plate parallel to the stream. Thus from Townsend (Reference 6), $f(y)$ is a Gaussian function given as

$$f(y) = \exp \{ - \sqrt{\pi/2} \cdot \frac{R_T'}{C_D} \cdot \frac{y^2}{(x - x_o) D} \} \tag{14}$$

where x_o is the origin of the turbulent boundary layer, R_T' is a constant which is representative of the large eddy structure, C_D is the coefficient of drag, and D is a characteristic dimension of the body.

The value of the drag coefficient can be shown to be a function of the momentum thickness, θ , at the point of cavity formation and of a characteristic dimension so that, $C_D \simeq \text{constant} \cdot (\theta/D)$. The length of the turbulent boundary layer can be approximated by the length of the cavity so that

$$f(y) = \exp \{ - \text{constant} \cdot \frac{y^2}{L \cdot \theta} \} \quad . \tag{15}$$

Now integrating for the mass flowrate and ignoring the higher order terms, yields

$$\dot{M}_{DG} = \pi D_M \cdot \Delta C \cdot U_\infty \cdot \{\text{constant} \sqrt{\theta \cdot L}\} \tag{16}$$

which gives a relationship for the mass diffusion rate as

$$\dot{M}_{DG} = \text{constant} \cdot \Delta C \cdot D_M \cdot V_\infty \cdot \sqrt{(1 + \sigma) \cdot L \cdot \theta} \tag{17}$$

where $\Delta C = (P_{FS} - P_G) \times \frac{6.24 \times 10^{-5}}{\beta} \, \text{lb}_m/\text{ft}^3$ in water. The momentum thickness,

θ , and the characteristic diameter of the cavity, D_M , are to be evaluated for the particular model geometry.

For the case of a gas being injected into an existing natural cavity, the net volume flowrate for the final ventilated cavity can be obtained from an analysis of the mass flowrates given as

$$\dot{M}_{T_f} = \dot{M}_{VG_f} + \dot{M}_{V_f} + \dot{M}_{DG_f} \qquad (18)$$

where the final cavity vapor mass flowrate $\dot{M}_{V_f}$, and part of the final diffused gas mass flowrate $\dot{M}_{DG_f}$, are due to the presence of an initial cavity. The final mass flowrates $\dot{M}_{V_f}$ and $\dot{M}_{DG_f}$ can be related to the ventilated gas flowrate by Equation (5) as

$$\dot{M}_{V_f} = \dot{M}_{VG} \cdot \frac{P_{V_f}}{P_{VG}}$$

$$\dot{M}_{DG_f} = \dot{M}_{VG} \cdot \frac{P_{DG_f}}{P_{VG}} \qquad (19)$$

and substituting into Equation (18) yields

$$\dot{M}_{T_f} = \dot{M}_{VG_f} \{ 1 + \frac{P_{V_f} + P_{DG_f}}{P_{VG_f}} \} . \qquad (20)$$

This result for the total mass flowrate can be expressed in terms of the final cavity pressure as

$$\dot{M}_{T_f} = \dot{M}_{VG_f} \{ 1 + \frac{P_{V_f} + P_{DG_f}}{P_{C_f} - (P_{V_f} + P_{DG_f})} \} \qquad (21)$$

where P_{DG_f} must be estimated by applying Equation (17), and P_{V_f} can be obtained at saturation conditions through steam tables. If the final gas pressure of the total noncondensable gas in the cavity is approximately equal to the partial pressure due to the concentration of the free stream, Equation (21) becomes

$$\dot{M}_{T_f} = \dot{M}_{VG_f} \{1 + \frac{P_{V_f}}{P_{C_f} - P_{V_f}}\} \qquad (22)$$

since P_{DG_f} is approximately zero. Finally, the volume flowrate can be obtained by using ideal-gas relationships, and the ventilated flow coefficient determined.

Experimental Investigations

The purpose of the experimental investigation was to first measure the ventilated flow coefficient for a developed cavity as a function of the flow parameters with minimal diffusion or vaporization occurring in the cavity, and then compare these flow coefficients to 1) experimental data obtained with diffusion occurring corrected by Equation 17 and 2) experimental data obtained with an initial natural cavity corrected by Equation 22. These investigations were conducted in the 12-inch water tunnel of the Applied Research Laboratory at the Pennsylvania State University. A detailed description of the facility is given in Reference 7.

Tests were conducted for two model geometries, the zero-caliber and quarter-caliber ogives, as shown in Figure 12. Model diameters of 0.50, 0.25, and 0.125 inches were run at 30, 45, and 60 ft/sec. over various cavity lengths at room temperature.

For the case of determining the ventilated flow coefficient with negligible diffusion and vaporization occurring in the cavity, the static pressure was adjusted so that the total cavity gas pressure for a given flow condition was equal to the saturation pressure corresponding to the air content of the free stream as measured by a Van Slyke apparatus. In addition, this static pressure was high enough to eliminate the possibility of vaporization. The resulting flow coefficients as determined by a gas flowmeter are shown in Figures 2 to 4 for the zero-caliber ogive in Figures 5 to 7 for the quarter-caliber ogive.

Measured ventilated flow coefficients obtained with significant gas diffusion and vaporization occurring in the cavity are shown in Figures 8 to 11. As can be observed in the figures, these additional cavity flowrates cause significant variation in the value of the ventilated flow coefficient.

For the case of an existing partial cavity, ventilated flow coefficients were measured for the 0.50-inch diameter zero-caliber ogive. A specific cavity length was obtained for a given flow condition by ventilating an existing cavity. Upon obtaining the final cavity size, the pressure was approximately equal to the saturation pressure corresponding to the air content of the free stream. Thus, Equation 22 was applied to correct the ventilated flow coefficient data. The corrected and uncorrected results are shown in Figure 8. A brief comparison indicates that the 0.50-inch diameter zero-caliber has identical corrected characteristics as the other diameters of the family, which the uncorrected points do not show.

Diffusion results were obtained for both the 0.25 and 0.125-inch diameter zero-caliber ogives. The cavity gas content was oversaturated or undersaturated

relative to the free-stream air content level. Some of the results are shown in Figures 9 to 11. In these figures, the data are corrected by applying Equation 17 with the parameters D_M and θ estimated for the particular flow configuration. For these cases, the momentum thickness was assumed to be given by a turbulent boundary layer model,

$$\theta = \frac{.036\ x}{\left(\frac{V_\infty \cdot x}{\nu}\right)^{1/5}} \tag{23}$$

where the distance x can be approximated by the model diameter. This gives a relationship for the mass diffusion rate as

$$\dot{M}_{DG} = \text{constant} \cdot \Delta C \cdot (1 + \sigma)^{1/2}\ (L)^{1/2}\ (D_M)^{1.6}\ (V_\infty)^{.9}\ (\nu)^{.1} \tag{24}$$

where D_M is of order of the model diameter, and $\Delta C = (P_{FS} - P_G) \times 6.24 \times 10^{-5}/\beta$ lb_m/ft^3 is the concentration gradient in water. Finally, the constant was determined from a measured point. This resulting equation was then applied to all cases and the corrected data compare favorably with the data for a purely ventilated cavity.

The corrected results illustrate the rapid change in ventilated flow coefficient as the cavitation number varies, and show similar dependence on cavity length, model diameter, and velocity. These trends are in qualitative agreement with the results of Swanson and O'Neill (1), and Cox and Claydon (3).

SCALING CONSIDERATIONS

Variations in the ventilated flow coefficient can be significant if gas diffusion and vaporization effects are not considered. However, once these effects are accounted for, the ventilated flow coefficient is a single valued function of the flow parameters. Thus, a possible scaling relationship can be derived by curve-fitting the experimental data which will calculate the ventilated flow coefficient for a particular model shape.

From the geometry of the flow field and the consideration that the diffusion was negligible, there are three possible parameters that could be used to describe similarity, namely Reynolds number, Froude number, and the non-dimensional geometry parameter , L/D . Thus, the ventilated flow coefficient can be expressed as

$$C_Q = \text{constant} \cdot f(Re, Fr, L/D) \tag{25}$$

for a particular geometric shape. In this relationship, the Reynolds number and Froude number are a function of model diameter. This is similar to the correlation made by Reichardt (2) employing the Froude number and maximum cavity diameter.

Using the non-dimensional geometry parameter, L/D, in scaling the flow coefficient is equivalent to using the cavitation number, σ, defined as

$$\sigma = \frac{P_\infty - P_C}{1/2 \rho V_\infty^{\,2}}$$

since, σ is a function of (L/D) for the zero- and quarter-caliber families (Reference 5).

The best fit of Equation (22) to the data is given by

$$C_Q \simeq K \cdot (L/D)^{.60} \cdot \left(\frac{V \cdot D}{\nu}\right)^{.52} \cdot (V/\sqrt{gD})^{.37} \tag{26}$$

for the quarter caliber family and by

$$C_Q \simeq K\, (L/D)^{.72} \cdot \left(\frac{V \cdot D}{\nu}\right)^{.21} (V/\sqrt{gD})^{.07} \tag{27}$$

for the zero caliber family. These scaling relationships are plotted as solid lines on the figures. A comparison of experimental and scaling results indicate good agreement. Also, the scaling relationships indicate a strong dependence on geometry (L/D), and a weaker dependence on Froude number. The Reynolds number becomes increasingly important as the bodies become more streamlined.

CONCLUSION

Variations in ventilated flow coefficients have been observed by many investigators. This paper shows that these variations can be caused by gas diffusion and vaporization into the cavity. Accounting for these effects is necessary in order to obtain the ventilated flow coefficient as a single-valued function of the flow parameters.

A method has been developed to obtain the fully ventilated flow coefficient without diffusion or vaporization occurring in the cavity. Also a theoretical method has been developed which can be applied to correct the experimental results if other processes exist in the cavity. A comparison between the corrected results and the pure ventilated flow coefficients indicate good

agreement. In all cases, the ventilated flow coefficient increased with decreasing cavitation number, and increased with increasing velocity.

A scaling group of geometry (L/D), Reynolds number, and Froude number has been found to describe the characteristics of a particular family.

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NOMENCLATURE

C_Q = ventilated flow coefficient

C_∞ = dissolved air content of free stream in ppm by moles

D = diameter of model

D_M = characteristic dimension of cavity diameter

$\dot{M}_{DG}$ = diffused gas mass flowrate

$\dot{M}_I$ = initial mass flowrate

$\dot{M}_T$ = total mass flowrate

$\dot{M}_V$ = vapor mass flowrate

$\dot{M}_{VG}$ = ventilated gas mass flowrate

P_{DG} = diffused gas pressure

P_{FS} = partial pressure of air based on free stream air content level

P_G = partial pressure of noncondensible gas

P_V = vapor pressure

P_{VG} = ventilated gas pressure

P_∞ = static pressure of free-stream

Q = volume flowrate

NOMENCLATURE (continued)

R	=	gas constant
U	=	velocity
V_∞	=	free stream velocity
σ	=	cavitation number
ν	=	kinematic viscosity

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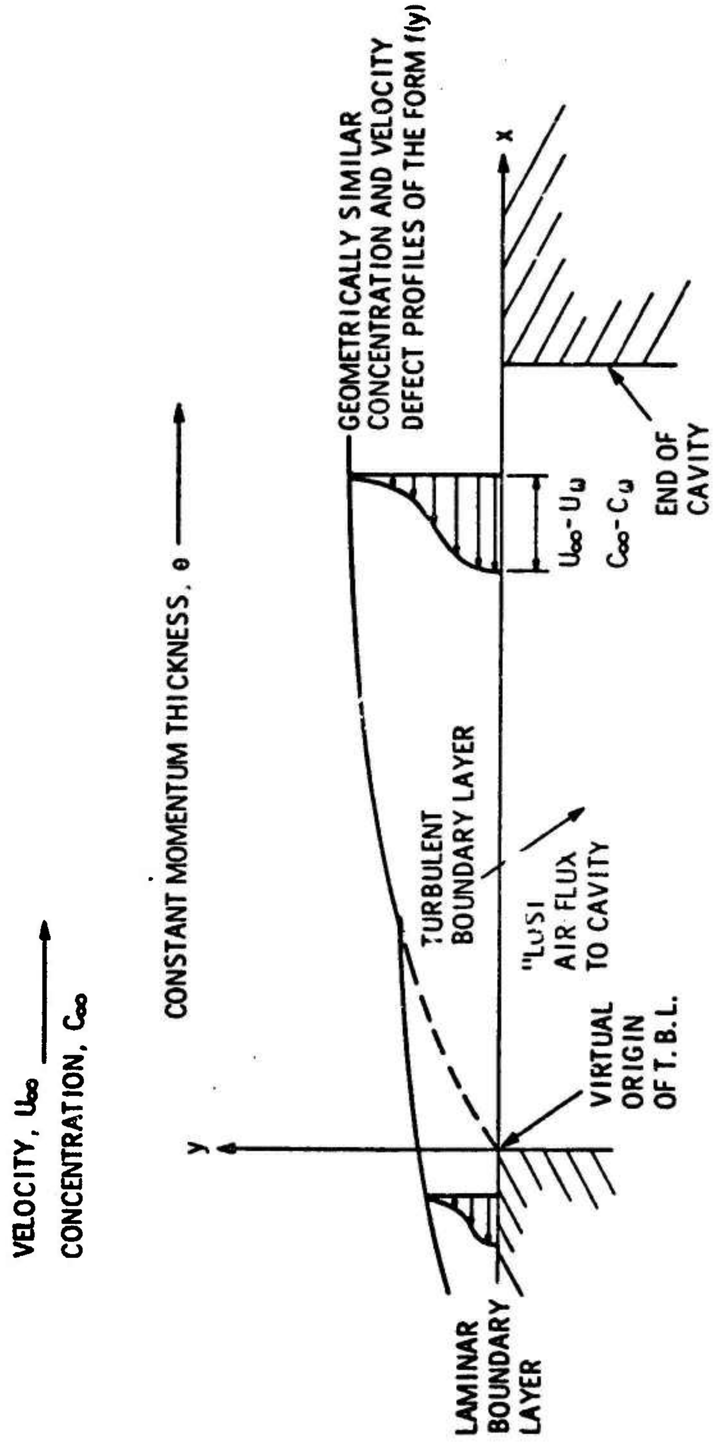

Figure 1: Schematic for an Undersaturated Cavity

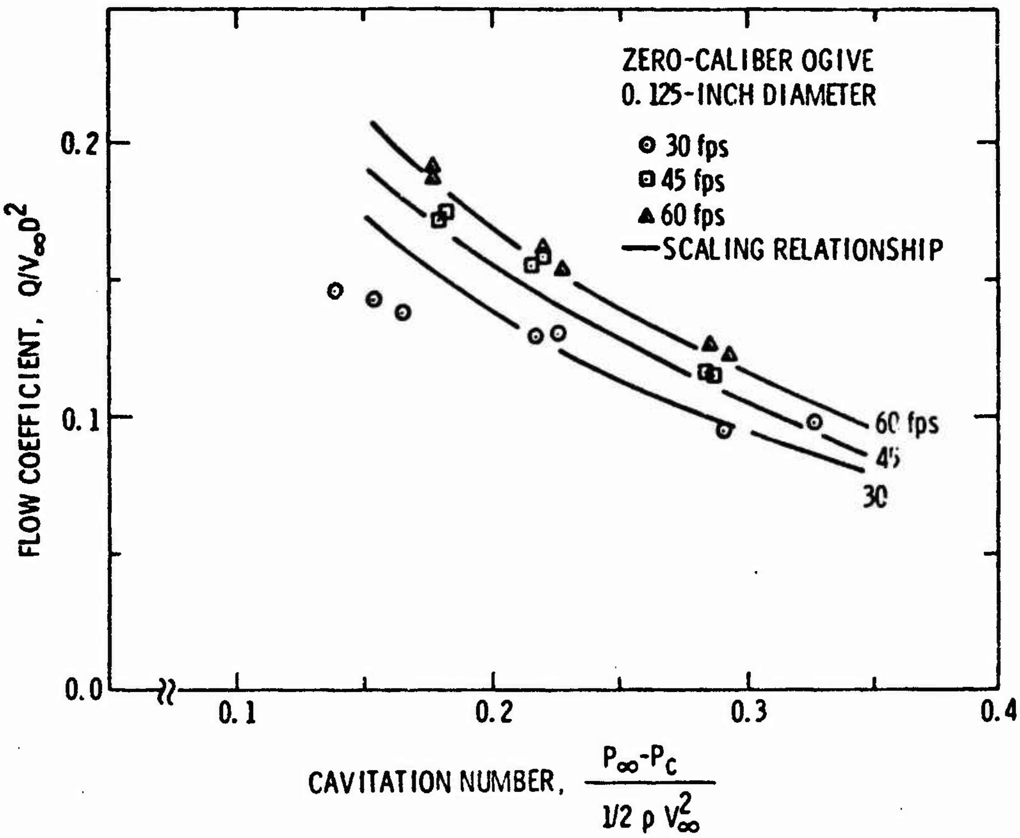

Figure 2: Flow Coefficient Data for 0.125-inch Diameter Zero-Caliber Ogive

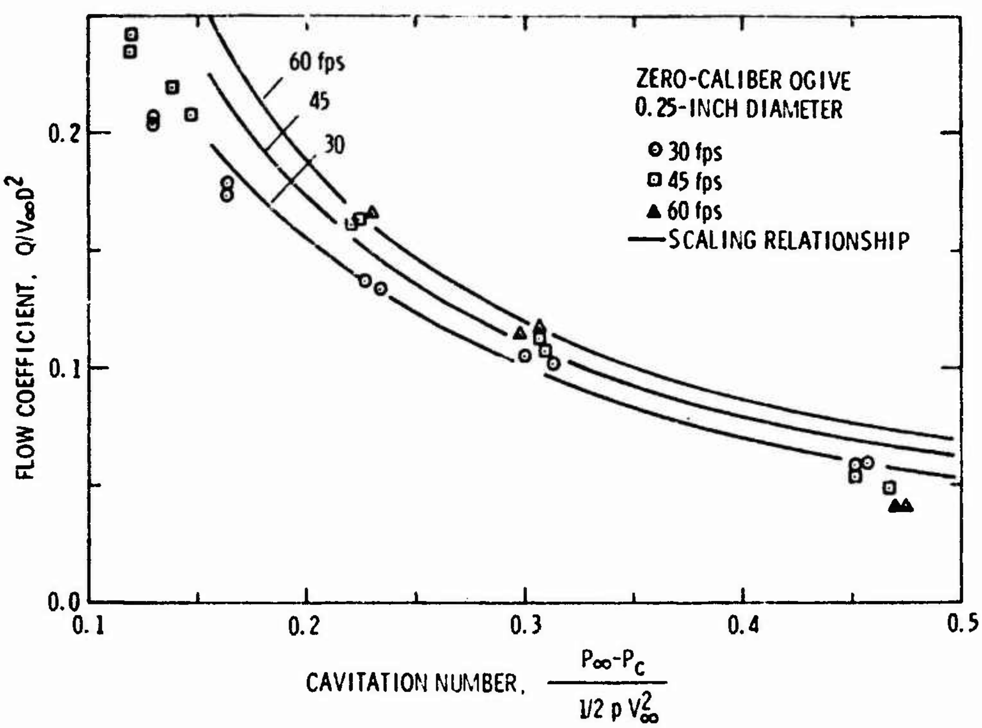

Figure 3: Flow Coefficient Data for 0.25-inch Diameter Zero-Caliber Ogive

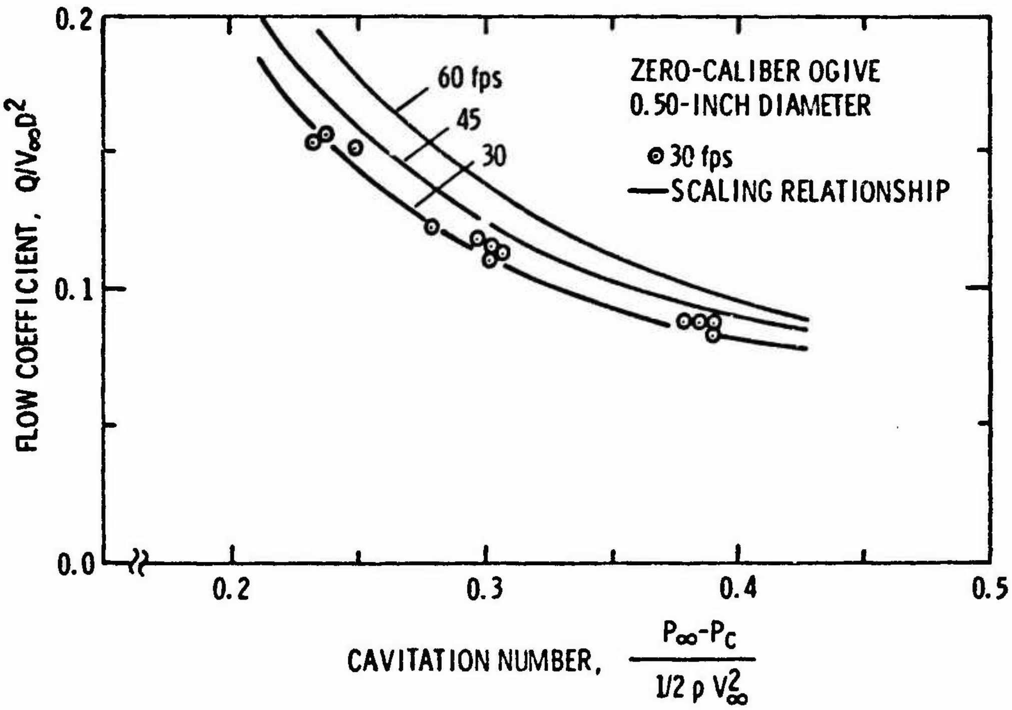

Figure 4: Flow Coefficient Data for 0.50-inch Diameter Zero-Caliber Ogive

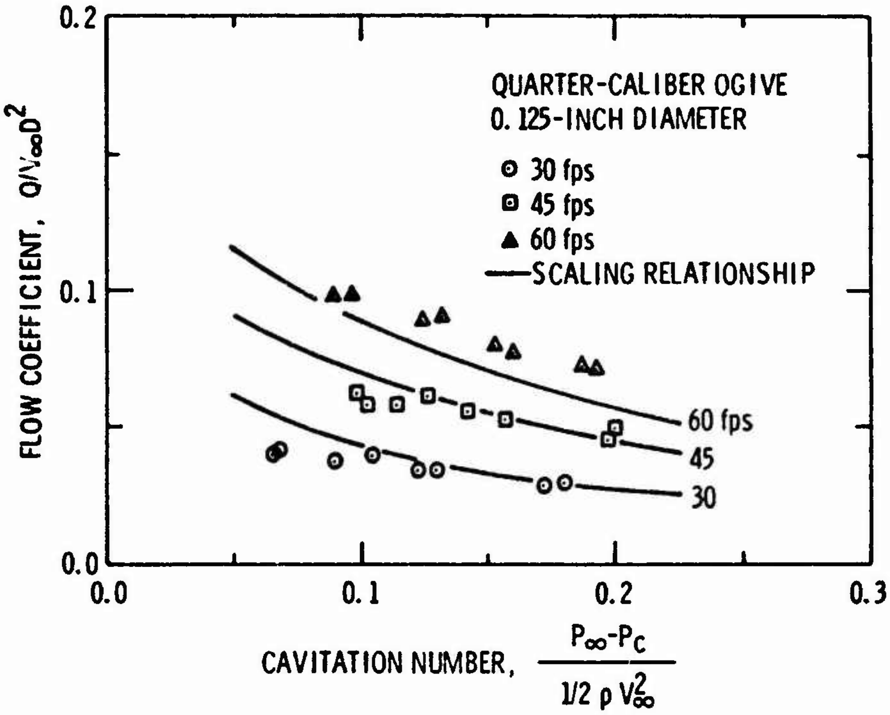

Figure 5: Flow Coefficient Data for 0.125-inch Diameter Quarter-Caliber Ogive

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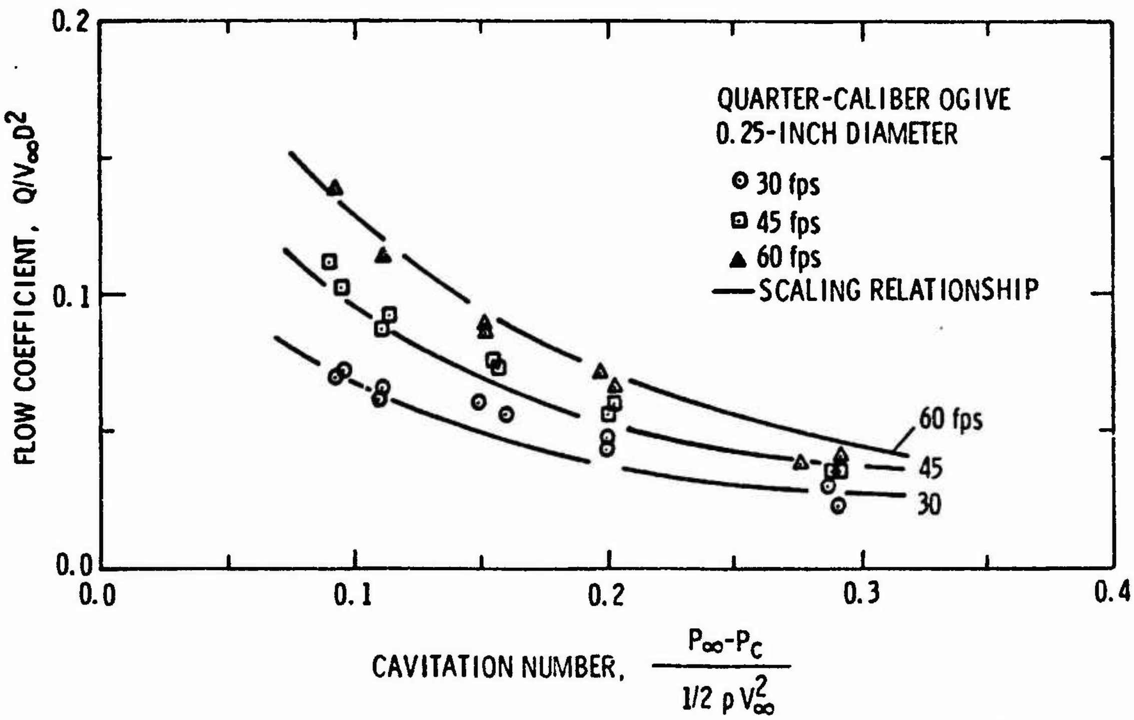


Figure 6: Flow Coefficient Data for 0.25-inch Diameter Quarter-Caliber Ogive

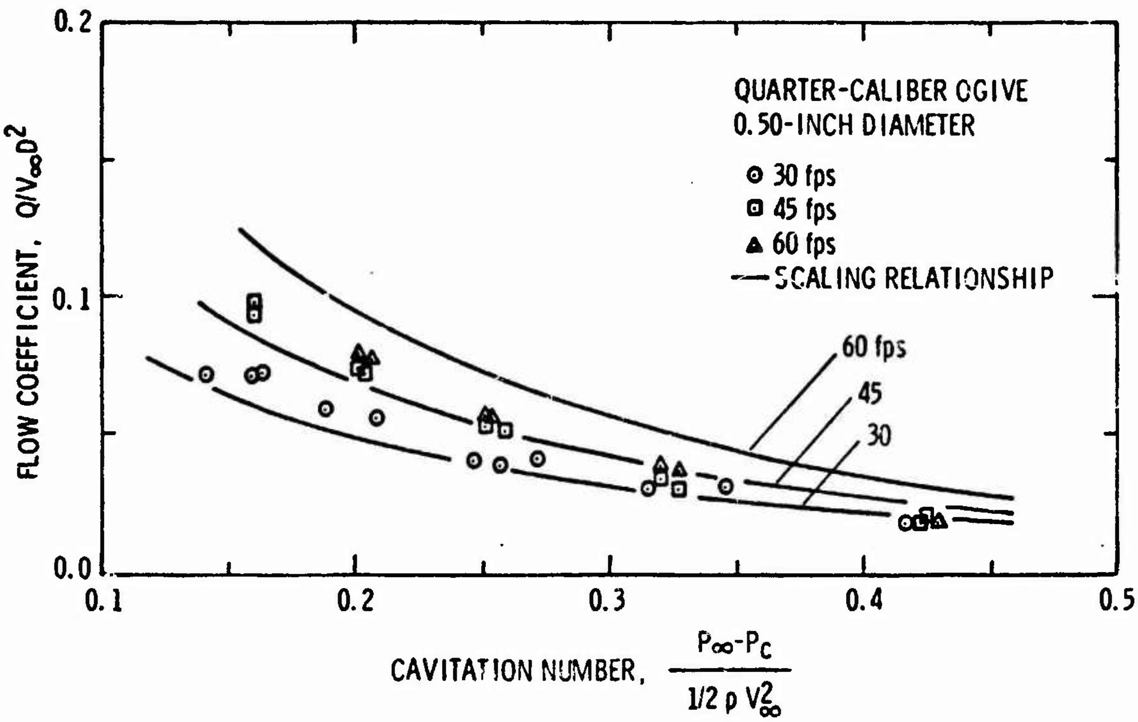


Figure 7: Flow Coefficient Data for 0.50-inch Diameter Quarter-Caliber Ogive

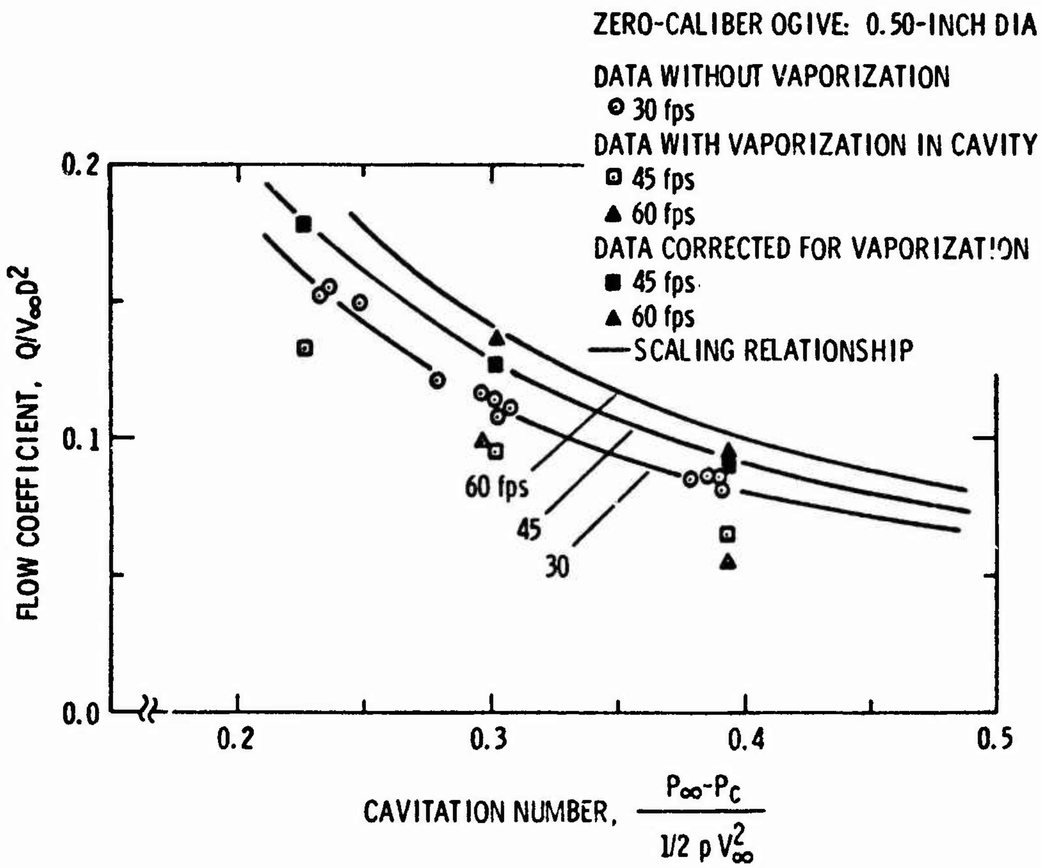


Figure 8: Flow Coefficient Data with a Partial Cavity for 0.50-inch Diameter Quarter-Caliber Ogive

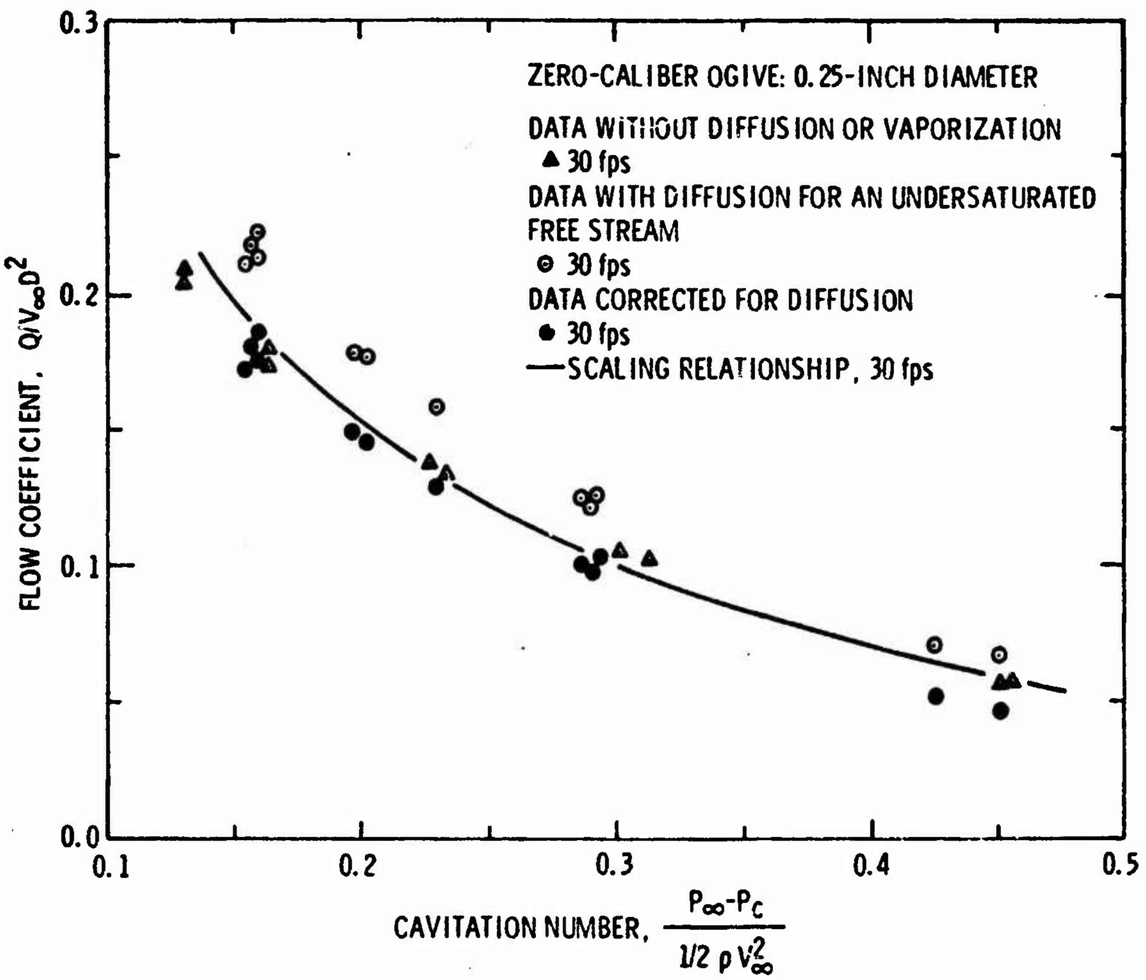


Figure 9: Flow Coefficient Data with Diffusion for 0.25-inch Diameter Zero-Caliber Ogive for 30 ft/sec.

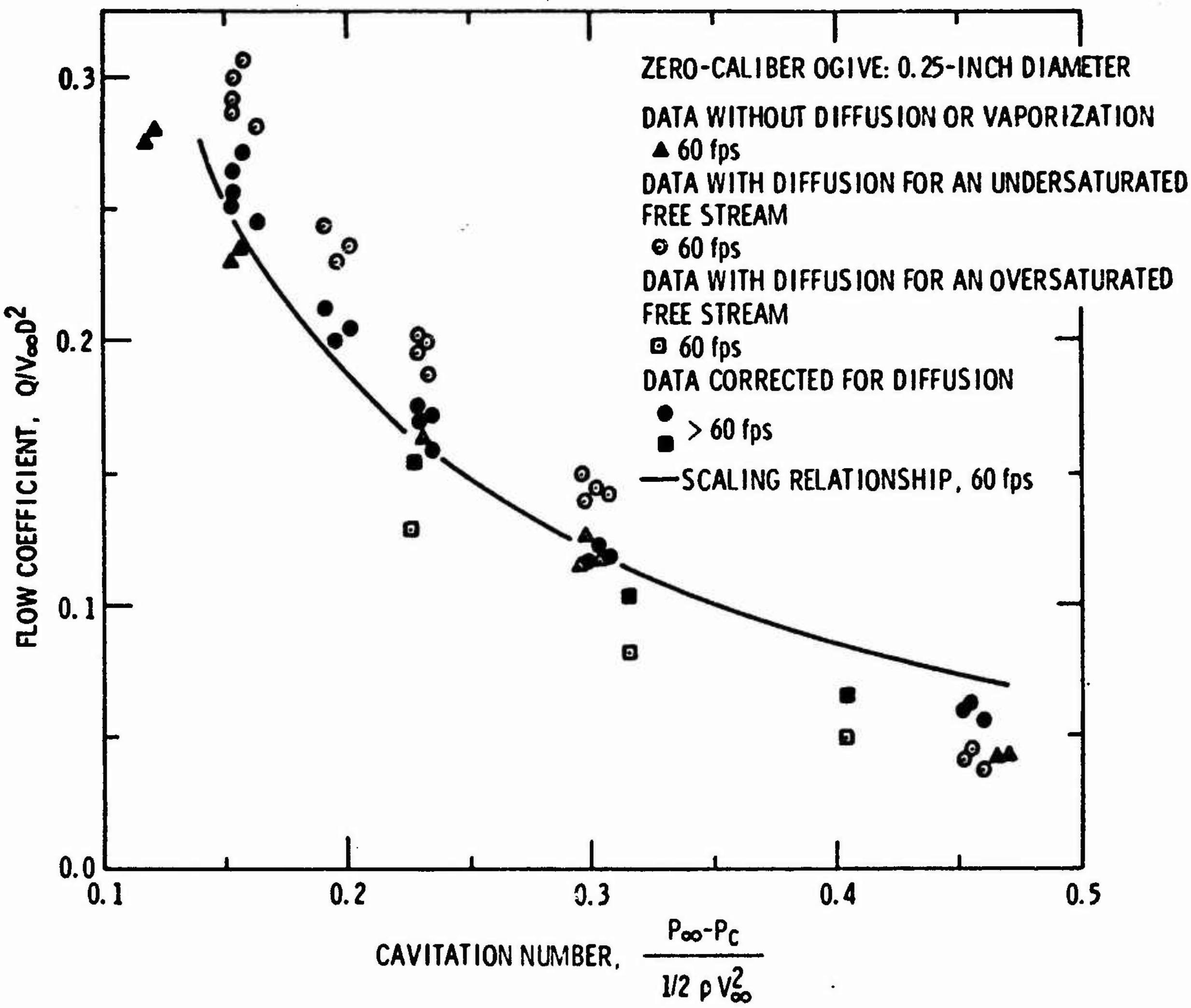


Figure 10: Flow Coefficient Data with Diffusion for 0.25-inch Diameter Zero-Caliber Ogive for 60 ft/sec.

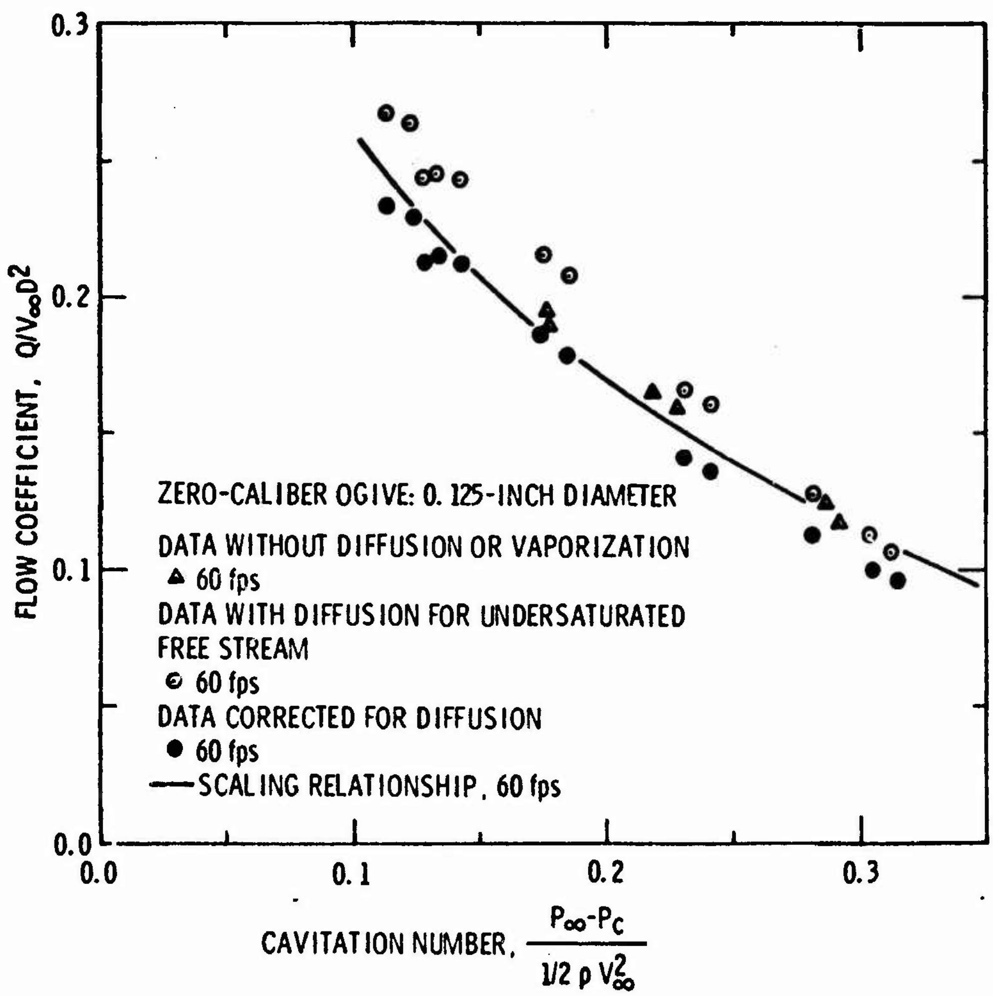
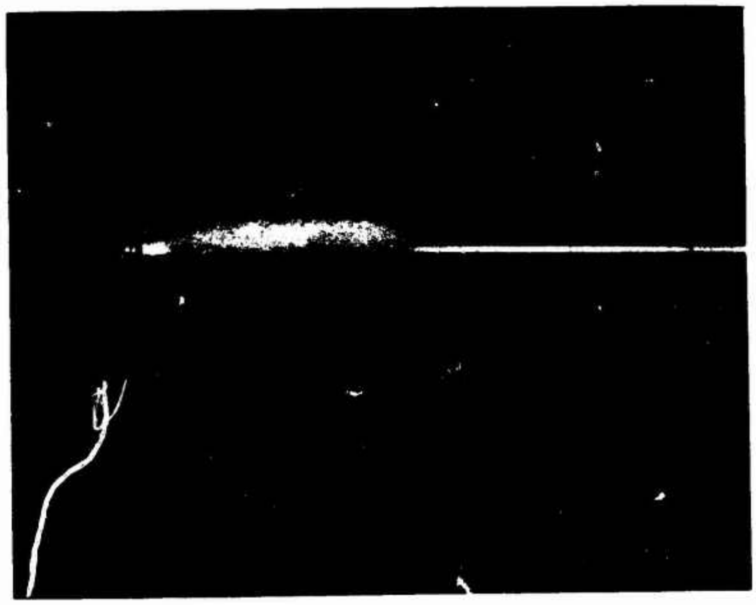


Figure 11: Flow Coefficient Data with Diffusion for 0.125-inch Diameter Zero-Caliber Ogive for 60 ft/sec.



0.50-inch Diameter
Quarter-Caliber Ogive

0.25-inch Diameter
Zero-Caliber Ogive

Figure 12: Photographs of Ventilated Cavities